

Strategic Thrust 6 Assured Autonomy for Aviation Transformation

Autonomy is the ability to achieve goals while operating independently from external control. (adapted from 2015 NASA OCT Roadmap)

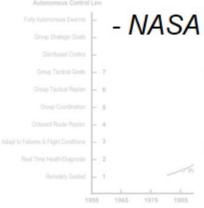
- Supervision Level
- · Goal Specification Level
- World View
- · Collaboration Level

- Deliberative Layer
 - Risk Awareness
- Habitual Layer
 Adaptivity
- · Reflexive Layer
- Quick responsiveness

along the s with the ab autopiloted unmanned sophisticate the extreme The objective of Strategic Thrust 6 is to enable autonomous systems that employ highly intelligent machines to maximize the benefits of aviation to society.



nation Levels



- NASA Aeronautics Strategic Implementation Plan, 2015

utomation

- Emphasis on human/machine continuum over self-governance continuum
- Emphasis on societal benefits

is relative in the sense that stood [only] with respect to I system – NASA us Systems Scoping Team

(from DoD Unmanned Aircraft Systems Roadmap, 2005

Why Autonomy?



2014 NRC Report*

- The burgeoning industrial sector devoted to the design, manufacture, and sales of increasing autonomy systems is indicative of the perceived economic opportunities that will arise.
- Civil aviation is on the threshold of potentially revolutionary changes in aviation capabilities and operations associated with increasing autonomy systems.

Unique Challenges

- Divergent opinions regarding technical feasibility of advanced autonomy
- NRC Report: "These systems, however, pose serious unanswered questions about how to safely integrate these revolutionary technological advances into a wellestablished, safe, and efficiently functioning NAS..."
- Traditional approaches to research, development, and implementation in aviation might not apply to autonomy
- Autonomy may create new markets and value networks, eventually disrupting existing ones and displacing earlier technologies
- Many non-technical barriers in aviation (economic, socio-cultural, potential for adverse consequences)

^{*} Committee on Autonomy Research for Civil Aviation; Aeronautics and Space Engineering Board; Division on Engineering and Physical Sciences; National Research Council: Autonomy Research for Civil Aviation:

Toward a New Era of Flight. National Academies Press, 2014.

Autonomy is Required to Enable a Long-Term Aviation Vision



- Anyone can safely fly any time and anywhere...
- with high confidence...
- in a fraction of the time it takes today...
- while sharing the sky with 1,000 times more vehicles than today...
- as some of those vehicles accomplish new missions...
- in close proximity to people and property...
- without harming the environment.

- Autonomy will foster a radical increase in aviation efficiency, reliability, and dependability through system-wide operational planning and highly responsive replanning to changes
- The aviation system will be so large and complex that it would be unmanageable without machine intelligence
- Autonomous machines will achieve unprecedented agility through high-bandwidth sensing, replanning, reconfiguration, and control
- Networked multi-vehicle systems will collaborate to achieve new goals
- Machine intelligence will enable new types of vehicles and missions, unconstrained by the requirements of today's conventional vehicles
- Autonomy will augment human abilities and make some tasks easier for humans, allowing machines to assist us and safely work among us
- Configured by autonomous systems, vehicles will continuously operate at peak performance and efficiency

Outcomes, Benefits, and Capabilities



2015	5 2	2025	2035
Outcomes	Introduction of aviation systems with bounded autonomy, capable of carrying out function-level goals	Introduction of aviation systems with flexible autonomy based on earned levels of trust, capable of carrying out mission-level goals	Introduction of distributed collaborative aviation systems with assured autonomy, capable of carrying out policy-level goals
Benefits	Efficiency and NAS capacity Increased robustness and resilience in operations Enhanced vehicle performance Initial UAS applications benefits	Increased NASA system flexibility, efficiency and capacity Prognostic safety New vehicles designed to leverage autonomy Reduced costs at all levels Multi-vehicle UAS applications benefits	Extreme flexibility and adaptability for large-scale systems, with extreme levels of reliability and recovery from disturbances Advanced prognostic safety Further reduced costs at all levels
Capabilities/ NASA Outputs	Advanced prescribed automation and initial goal-directed and adaptive automation Initial world views from local sensors and limited data exchange Applied to aviation system components and small-scale systems. Predominantly human-supervised; higher levels of machine independence under carefully controlled conditions	Mission-level goal-directed adaptive automation Large-scale detailed world views using advanced sensors and networks Applied to large-scale integrated systems Human/machine teams with many levels of control, depending on specific situations; extensive machine-based learning	Campaign-level goal-directed adaptive automation, embedded within all system elements Adaptive collaboration based on extensive shared world views Highly distributed large-scale collaborative systems that constitute integral parts of larger systems they support Human/machine teams, with humans primarily specifying strategic goals; many systems self-protect and self-heal

10-Year Vision for the Future of Civil Aviation



2025 capabilities provide early payoffs and vital steps toward the 2035+ future

- Based on earned levels of trust, intelligent systems perform many tasks previously performed by human operators, in the air and on the ground
- Natural language processing facilitates communication between humans and machines
- Reliable high-bandwidth low-latency communications enable vehicle-to-vehicle and vehicle-to-ground coordination
- UAS can act autonomously to avoid collisions with other air vehicles, terrain, and structures
- Semi-autonomous UAS traffic management services assure safety of low-altitude UAS operations
- Teams of UAS, managed by a small number of human operators, operate over large geographical areas
- Onboard systems autonomously monitor, assess, and predict vehicle states and vehicle needs
- Sensing, decision making, and execution systems are capable of assuming control of vehicles to prevent accidents
- Advanced learning and data analytics systems balance air traffic demand and airspace system capacity
- Operators and service providers collaborate using intelligent networked systems to continually optimize flight trajectories
- Optimized vehicle design and manufacturing processes reduce certification time and cost

Roadmap Elements



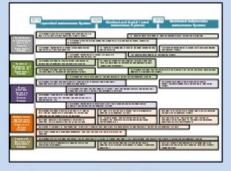
Three parallel and interdependent elements to achieve the Vision





Advancement Strategies

Approaches employed by NASA to achieve aviation autonomy objectives



Research Challenges

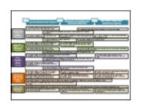
Technical activities to achieve knowledge breakthroughs and advance aviation autonomy capabilities



Mission Products

Targeted NASA and community capabilities that facilitate a viable path toward mature and widespread aviation autonomy





Previous Efforts Provide Firm Foundation for Research Challenges



NRC Report* Barriers

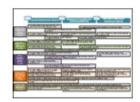
- Technology barriers
 - Communications and data acquisition
 - Cyberphysical security
 - Decision making by adaptive/nondeterministic systems
 - Diversity of vehicles
 - Human-machine integration
 - Sensing, perception, and cognition
 - System complexity and resilience
 - Verification and validation (V&V)
- Regulation and certification barriers
 - Airspace access for unmanned aircraft
 - Certification process
 - Equivalent level of safety
 - Trust in adaptive/nondeterministic IA systems
- Other barriers
 - Legal issues
 - Social issues

* Autonomy Research for Civil Aviation, 2014

ICAST* Research Themes

- Autonomous planning, scheduling, and decision making
- Real time multi-vehicle cooperation and interoperability
- Autonomous vehicle control, health management, adaptation, and optimization
- Human-autonomy teaming
- Secure command and control
- System wide status and assessment
- Autonomy infrastructure and information management
- Verification, validation, and certification of autonomous systems
- Test and evaluation capabilities
- Design and analysis of autonomous systems

^{*} ARMD Inter-Center Autonomy Study Team briefing, 2014



Research Challenges



Research is organized into five research themes

- 1. Technologies and Methods for Design of Complex Autonomous Systems
 - Methods and technologies for design of intelligent machine systems capable of operating and collaborating in complex environments
- 2. Assurance, Verification, and Validation of Autonomous Systems
 - Methods for certification and assuring trustworthiness in the design and operation of autonomous systems
- 3. Human-Autonomy Teaming in Complex Aviation Systems
 - Optimal human-machine role assignments and teaming strategies for increasing machine autonomy and earned levels of trust
- 4. Implementation and Integration of Autonomous Airspace and Vehicle Systems
 - Novel real-world autonomy applications and transition paths toward higher levels of autonomy
- 5. Testing and Evaluation of Autonomous Systems
 - Metrics, models, simulation capabilities, and testbeds for assessment of autonomous systems in laboratory and operational settings.

Strategic Thrust 6 Research Challenges



2015 2025 2035 Introduction of aviation systems with bounded Introduction of aviation systems with flexible Introduction of distributed collaborative autonomy, capable of carrying out functionautonomy based on earned levels of trust. aviation systems with assured autonomy, Research level goals capable of carrying out mission-level goals capable of carrying out policy-level goals Themes 1A. Develop machine intelligence design methods that are 1F. Develop design methods for adaptive/non-deterministic machine intelligence robust to system failures and system integrity threats Develop machine intelligence design methods for unforeseen events in complex Technologies environments and Methods for Design of Develop technologies to support machine sensation, 1E. Develop technologies to support machine reasoning and Complex perception, and low-level cognition decision making Autonomous Develop technologies to support system-state Systems 1G. Develop technologies for self-healing systems management and optimization Develop technologies to support collaboration between autonomous systems 2A. Develop methods for characterizing the behavior of 2D. Develop methods and standards for maintaining realincreasingly autonomous and collaborative systems time trustworthiness of increasingly autonomous systems Assurance, in complex environments Verification, and Validation of 2B. Develop methods and standards for assuring 2E. Develop methods and standards for maintaining real-time trustworthiness of adaptive/non-Autonomous trustworthiness of increasingly autonomous systems deterministic collaborative systems Systems 2C. Develop certification methods for safe deployment of increasingly autonomous systems 3A. Develop methods and guidelines for assigning roles to humans and increasingly 3E. Develop methods to determine which human autonomous systems in realistic operating conditions capabilities remain necessary / add value to the aviation system Human-3D. Develop methods and technologies to support teaming between humans and increasingly Autonomy autonomous systems in normal and non-normal operations Teaming in Complex 3B. Develop framework for introducing increasingly autonomous systems that matches role and authority with Aviation earned levels of trust Systems 3C. Develop technologies to enable real-time situation understanding between human operators and increasingly autonomous 4A. Develop methods to evaluate the viability & impacts 4E. Identify infrastructure to support flexible, large-scale, 4G. Identify infrastructure to support adaptive, system-wide (e.g., societal, economic, technological) of increasingly cooperative autonomous systems collaborative autonomous systems autonomous aerospace vehicles & operations Implementation 4F. Select, develop, and implement applications of and Integration 4H. Select, develop, and implement applications of 4B. Select, develop, and implement applications of autonomy that enable flexible, large-scale aerospace autonomy that enable adaptive, collaborative aerospace of Autonomous autonomy that are compatible with existing systems vehicle cooperation operations on a system-wide scale Airspace and Vehicle 4C. Develop framework for co-development of policies, standards, and regulations with development and deployment of increasingly autonomous systems Systems 4D. Assess candidate technology development and transition paths for the future of aviation autonomy Testing and 5A. Develop metrics, methods and capabilities to assess feasibility, safety, resilience, robustness, trust, performance, and human interactions with increasingly autonomous systems Evaluation of

5C. Test, evaluate and demonstrate selected flexible,

operations

cooperative applications of autonomy to support large-scale

5B. Test, evaluate & demonstrate selected small-scale

applications of autonomy

Autonomous

Systems

____0

5D. Test, evaluate and demonstrate selected adaptive.

wide operations

collaborative applications of autonomy to support system-



Advancement Strategies



- Address critical autonomy barriers that require unique NASA contributions
- Leverage initial technologies to insert autonomy into operational environments, and then build on experience (Evolutionary Autonomy)
- Develop and demonstrate radical breakthrough autonomy concepts, technologies, and mission products (Revolutionary Autonomy)
- Advance autonomy technologies by developing mission products that leverage the explosive growth and rapid development cycles of unmanned aerial systems
- Leverage large investments in non-aviation autonomy technologies by repurposing those technologies for aviation
- Provide community coordination and leadership to achieve research advances and implement selected applications



Candidate Mission Products



- Candidate Mission Products: targeted capabilities to be achieved in Epoch 1 (2015-2025)
 - Described in terms of a specific products achievable by 2025
 - Provide focus for research and technology development
 - Provide near-term benefits as well as advancement paths toward ultimate objectives
- Mission Product selection
 - NASA has identified 17 candidate Mission Products based on 2025
 Vision, utilizing Advancement Strategies
 - Refinement and down-selection will be based on:
 - NASA/community dialogue
 - NASA goals and resources
 - Partnership potential



Candidate Mission Products (1 of 3)



1. Autonomy-Enabled Airborne Public Safety Services

Goal: Use autonomy technologies to improve safety and effectiveness of airborne public safety operations 2025 Product: Autonomy-augmented airborne medical services

2. Autonomy-Enabled UAS for Earth Science

Goal: Advance practical civil applications of collaborative UAS swarms

2025 Product: Brassboard capability to support multi-UAS NASA Earth Science missions

3. UAS Traffic Management and Operations

Goal: Safely enable large-scale UAS operations and provide a blueprint for autonomy-centric redesign of the National Airspace System

2025 Product: Autonomy-based concept and technologies for beyond-visual-line-of-sight civil operations of small UAS

4. Autonomous Airport Surface Operations

Goal: Establish a foundation for in-flight multivehicle collaborative autonomy using ground systems to enable optimal airport surface operations

<u>2025 Product</u>: Demonstrate an integrated multi-agent autonomous airport ground operations using initial collaborative autonomy and sensor technologies

5. Autonomy-Enabled Air Traffic Management

<u>Goal</u>: Advance development of large-scale autonomous decision systems that require integration of complex constraints and multi-agent coordination, through direct operational experience

2025 Product: Develop a human-supervised autonomous traffic flow management capability based on large data systems and data analytics

6. Collaborative In-Flight Optimization for Transport Aircraft

Goal: Advance collaborative autonomous air/ground traffic management concepts and technologies and provide an autonomy modernization path for existing IFR operations

<u>2025 Product</u>: Operational initial autonomy technologies applied to commercial aviation to facilitate in-flight trajectory optimization, trajectory negotiation, and vehicle teaming



Candidate Mission Products (2 of 3)



7. Autonomy-Enabled Flight Crew Performance in Complex Environments

<u>Goal:</u> Achieve optimal flight performance, pilot training, and operational resilience through human/cockpit systems that employ the specialized skills of operators and machine systems working as an optimized team 2025 Product: Cockpit technology prototypes and guidelines for autonomy-enhanced flight systems, teamed

2025 Product: Cockpit technology prototypes and guidelines for autonomy-enhanced flight systems, teamed human/machine decision making, and human/autonomy interfaces to enable transformational operations and mobility

8. Autonomy-Enhanced Vehicle Safety

Goal: Make flight vehicles situationally aware of their internal states so they are able to assume an independent role in safety assurance

2025 Product: Vehicle intelligence technologies that assess vehicle safety state, targeting high risk scenarios

9. Resilient, Trusted Autonomous Vehicle Systems

<u>Goal</u>: Achieve safe and reliable operations for autonomous aircraft by integration of resilient vehicle technologies <u>2025 Product</u>: A prototype scaled vehicle that demonstrates refuse-to-crash operation in selected off-nominal conditions through resilient design approaches, ability to deal with uncertainties, and appropriate response to off-nominal conditions

10. Inflight Vehicle Performance Optimization

<u>Goal</u>: Optimize vehicle performance and efficiency through automated and autonomous systems that determine the vehicle state and adaptively reconfigure

<u>2025 Product</u>: Demonstration of improved vehicle efficiency with less environmental impact through intelligent feedback between internal state monitoring and adjustment of vehicle parameters

11. Complex Decision-Making UAS

<u>Goal</u>: Develop autonomous vehicles with reasoning and decision making capabilities to independently and reliably make safety-related decisions in complex, uncertain environments

2025 Product: Demonstration of UAS that identifies loss of control in selected multiple simultaneous simulated faults and makes a decision to crash in a manner that does not impact property/personnel

12. Fully Autonomous Transport Aircraft

Goal: Understand CONOPS, technologies, and system requirements necessary for design, development, and operations of practical fully autonomous transport class civil aircraft

<u>2025 Product</u>: Design and demonstrate a fully autonomous aircraft to understand the full potential and costs of autonomy technology for transport class civil aircraft



Candidate Mission Products (3 of 3)



13. Mission-Adaptive, Eco-Friendly Autonomous Vertical Lift Vehicles

<u>Goal</u>: Design small-scale vertical lift vehicles to be safe, reliable, and eco-friendly through the application of autonomy technologies, and rapidly advance the state of maturity for autonomy technologies that improve vehicle design and vehicle operational safety and efficiency

<u>2025 Product</u>: A small-scale autonomous UAV with reliability and performance enhanced and environmental impacts reduced through use of autonomy-enabled design tools, and operational safety and utility improved through mission-adaptive health state awareness and prediction technologies

14. Infrastructure for Experimentation, Evaluation, and Testing of Autonomous Systems

<u>Goal</u>: Enable researchers in academia, industry, and government laboratories to provide consistent benchmarked experimental and evaluation data on autonomous system through well established methods, tools, and infrastructure <u>2025 Product</u>: Flexible infrastructure for experimentation, evaluation, and testing of autonomous systems and multi-agent collaborations

15. Initial Certification Standards for Autonomous Systems

<u>Goal</u>: Enable certification of autonomous aviation systems and provide verification and validation (V&V) techniques to support certification

<u>2025 Product</u>: Initial certification standards for runtime assurance and continuous certification approaches to V&V of autonomous systems, obtained by brokering consensus between regulators and industry.

16. Vehicle Structural Health for Maintenance and Safety

<u>Goal</u>: Integrate distributed structural sensor network data with models of individual vehicles to determine the structural health and impose necessary constraints on performance or mission

2025 Product: Digital Twin for autonomous sustainment/maintenance and real-time structural safety in flight vehicles

17. Autonomy-Enabled Concepts for Achieving the ATM+3 Vision

<u>Goal</u>: Advance autonomy technologies to enable future National Airspace System densities, diversities, efficiencies <u>2025 Product</u>: Stakeholder-vetted autonomy-enabled integrated air/ground concept alternatives that will enable millions of manned and unmanned platforms to operate in U.S. airspace in a safe and efficient manner



Candidate Mission Product Summary Description Example

All Mission Product descriptions are available at http://www.aeronautics.nasa.gov/strategic-plan.htm

1. Autonomy-Enabled Airborne Public Safety Services

Goal and Benefits

- Product: Technology prototypes and procedures for improved safety and efficiency across a range of public safety operations
- Autonomy Goal: Promote public acceptance of autonomy through integration of autonomy-enabled capabilities that improve safety and effectiveness of airborne public safety operations
- Benefits
 - Reduced time to reach emergency sites and victims
 - · Increase in victim lives saved
 - Increase in structures/acres saved from fires
 - Decrease in relief delivery times (e.g., water, food, medical supplies)
 - Decreased time spent on airborne and ground-based asset coordination
 - Reduced accident rates for airborne public safety personnel

Concept

- Autonomous hazard awareness systems
 - Intelligent on-board hazard awareness capability recognizes and alerts pilots to obstacles, including power lines, trees, intruder vehicles, etc.; assesses and identifies safe landing zones
- · Intelligent decision support
 - Pre-flight and real-time in-flight decision support tools facilitate decisions to go/not go, continue, re-plan, or discontinue the mission by obtaining and jointly assessing environmental, mission, aircraft and flight crew parameters
- · Small Autonomous Public Safety Vehicles
 - Launch from larger airborne (mother ship) or ground-based assets to provide surveillance and site reconnaissance; and deliver immediate assistance and emergency supplies; while independently coordinating with other vehicles and services to avoid obstacles and assure airspace containment

Current-Day Challenges

- Safety
 - Helicopter Emergency Medical Services (HEMS) is among the highest-risk civilian occupations in the US (Blumen, 2009)
 - 77% of HEMS accidents weather-related or collisions with objects
 - Intruder drones pose a safety risk to EMS crews and delay getting victims to healthcare facilities (AAMS)
- Efficiency
 - For large-scale disaster relief, ensuring coordination of assisting assets dramatically slows relief efforts (FEMA, 2005)

Deliverables

- Concepts of operation, including policies, standards, regulations, and procedures
- · Prototype systems for autonomy functions
- · V&V of flight systems and operations within airspace
- · Human-autonomy teaming guidelines and technology

Partner Roles

NASA Role

- Identification and resolution of knowledge gaps
- Concepts and prototype technology development
- V&V procedures

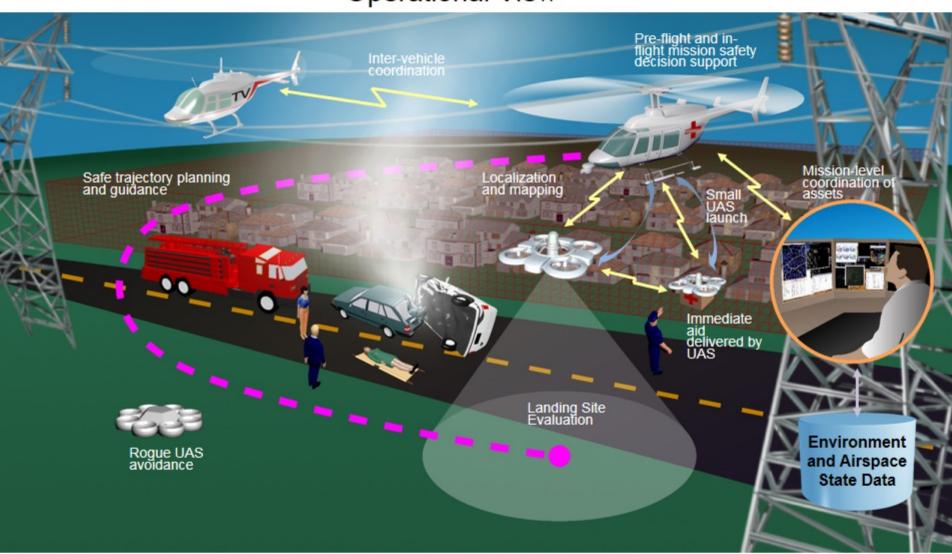
Industry Role

- UAS platforms , payload, and nav & control systems
- · Sensor and avionics systems for manned aircraft
- · Air/air and air/ground communication systems
- · Integration of prototype systems

Autonomy-Enabled Airborne Public Safety Services



Operational View



Summary and Status



- NASA ARMD is developing a roadmap to guide activities for Aeronautics Strategic Thrust 6: Assured Autonomy for Aviation Transformation
- Major elements of the roadmap are Advancement Strategies, Research Challenges, and Mission Products with outcomes that produce defined capabilities and benefits
- Due to the game-changing potential and fast-moving nature of autonomous systems, candidate Mission Products are focused primarily on Outcome 1 (2025), with an eye on advancement toward ultimate capabilities
- The roadmap will evolve based on engagement with the aviation community
- Execution will rely on collaborative partnerships to strategically leverage efforts and resources

Please Provide Feedback!



- Community feedback will be used to develop a revised draft, which will be complete in September 2016.
- All comments and questions will be addressed. To receive comments and NASA responses, please request to be added to the Thrust 6 mailing list by emailing us at

NASA-ARMD-Autonomy@mail.nasa.gov

 Feedback may be provided on line at https://nari.arc.nasa.gov/thrust6

- Questions to consider:
 - Does the roadmap address the critical research and technology barriers?
 - Are the advancement strategies appropriate?
 - Which mission product candidates are most important in advancing aviation autonomy? How can we make them more useful?
 - What roles should NASA and partners play in realizing the mission products?

Website for Roadmaps and Strategic Plan: http://www.aeronautics.nasa.gov/strategic-plan.htm